IMPROVED DROUGHT EARLY WARNING AND FORECASTING TO STRENGTHEN PREPAREDNESS AND ADAPTATION TO DROUGHTS IN AFRICA

DEWFORA

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White paper for definition of drought vulnerability across Africa

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SUMMARY

Like other natural hazards, the effects of drought have both a natural and social component. Defining vulnerability to drought is complex and involves some measure of susceptibility and coping capacity. Vulnerability to drought varies spatially and is determined by natural factors, like the intensity and magnitude of the drought hazard that lead to its susceptibility, and by social factors that lead to exposure, coping capacity and adaptive capacity. The social factors that define vulnerability to drought – for example number of people exposed, per capita water availability, water use trends, technology, policies, etc – change over time, therefore vulnerability also changes. As result, subsequent droughts in the same region will have different effects, even if they are identical in intensity, duration, and spatial coverage, because societal characteristics evolve through time.

This white paper provides a discussion of the methods for definition of drought vulnerability across Africa in the DEWFORA study. The methods proposed will then be used in the case studies and in the Arica-wide study to define drought vulnerability and will be incorporated in the early warning protocol. Here we propose that drought vulnerability incorporates natural and social aspects and their evolution over time. The indicators that characterise these aspects are presented and discussed. Finally, the document introduces the concept of thresholds to e defined in the case studies. The approach proposed has large value from the operational standpoint, since it links the hazard with the propagation of drought effects across water resources, water sectors and society. Nevertheless it is advisable that drought monitoring to concentrate the efforts on the first variables in the time chain in order to anticipate drought impacts. For this reason, diagnostic drought indicators based on precipitation are widely used for drought monitoring. They take advantage of the delay of the socioeconomic response function to drought and allow for the adoption of timely measures early on. In the context of a drought early warning system, the focus on vulnerability may prove to be very effective since it includes the evaluation of the capacity to anticipate and compensate the adverse effects of drought. If a drought forecast is available, drought managers gain time and can come closer to drought impacts in their analysis. The focus on drought vulnerability requires the development of new drought indicators that are tailor made for a given drought impact. This requires information about the dependency of regional and local communities on water use. In addition to hydro meteorological values, other variables that influence drought impacts can be included in the analysis. This simplifies the difficult task of identifying threshold values of indicators at which drought problems arise.

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1. OBJECTIVES AND COMMON TERMS

1.1 OBJECTIVES

This white paper provides a discussion of the methods for definition of drought vulnerability across Africa. The methods proposed will then be used in the case studies and in the Arica-wide study to define drought vulnerability and will be incorporated in the early warning protocol. Here we propose that drought vulnerability incorporates natural and social aspects and their evolution over time. The indicators that characterise these aspects are presented and discussed. Finally, the document introduces the concept of thresholds to e defined in the case studies.

Why common methodology for all Dewfora Partners? The main objective of Dewfora is to develop drought early warning systems in Africa; to that end, it is desirable to have a protocol for identifying drought vulnerability based on common concepts and definitions and methodologies.

1.2 THE CONCEPT OF DROUGHT

Drought is a natural hazard that differs from other hazards in that it has a slow onset, evolves over months or even years, affects a large spatial region, and causes little structural damage. Its onset and end, and the severity of drought are often difficult to determine. Droughts are a normal part of climate variability for virtually all regions.

Like other natural hazards, the effects of drought have both a natural and social component (UNISDR, 2004; Iglesias et al., 2009; Birkmann, 2007). Defining vulnerability to drought is complex and involves some measure of susceptibility and coping capacity (Birkmann, 2007; Iglesias et al., 2009).

Droughts differ from one another in three essential characteristics: intensity, duration, and spatial coverage. Intensity refers to the degree of the precipitation shortfall and/or the severity of impacts associated with the shortfall. Intensity also determines the deficit of water that causes the observed drought impacts. It is generally measured by the departure of some climatic index from normal and is closely linked to duration in the determination of impact. Another distinguishing feature of drought is its duration that can range from very short periods to years. The magnitude of drought impacts is closely related to the timing of the onset of the precipitation shortage, its intensity, and the duration of the event.

Droughts also differ in terms of their spatial characteristics. The areas affected by severe drought evolve gradually, and regions of maximum intensity shift from season to season. From a planning perspective, the spatial characteristics of drought have serious implications.

Definitions of drought reflect many disciplinary perspectives and therefore incorporate different physical, biological, and socioeconomic variables. Drought is often classified into four types: meteorological, agricultural, hydrological, and socioeconomic. Meteorological drought refers to a precipitation shortage from average; agricultural drought results when the precipitation shortage results in a deficit of soil moisture and therefore produces agricultural impacts derived from the water deficit in the vegetation; hydrological drought results when the deficit in precipitation extends to large periods and therefore there is a shortfall on surface or subsurface water supply. Finally, socioeconomic drought is often referred to when the deficit precipitation or water shortage has an impact on the economy and society.

1.3 A GLOSSARY OF COMMON TERMS

Although it is clear that the social and natural dimensions of drought are determinants of vulnerability, analysts often adopt different definitions. Here we summarise the main concepts that are used in this document and in the Dewfora project with the aim of establishing a common language across the many components of the project and reach practical results (Table 1).

Table 1 A short glossary of terms used in the DEWFORA study

Concept	Definition
Hazard	The probability of occurrence of a potentially damaging physical event which may cause social, health and economic losses or environmental degradation. The hazard is extrinsic to the system or object at risk.
Susceptibility	A measure of the fragility of the object at risk from a damaging event (e.g. the likelihood of a building to collapse due to the impact of an earthquake).
Coping capacity	The ability or potential of a system to respond successfully and recover from the impacts caused by an adverse event.
Vulnerability	Is a measure of the consequences suffered by an object exposed to an adverse event. Vulnerability is intrinsic to the object at risk and is a function of susceptibility and coping capacity.
Exposure	Exposure is a measure of the size of the system exposed to drought, it is measured as damage (number of people, economic goods, or ecosystems) caused by drought impacts.
Risk	The expected harmful consequences, or losses resulting from interactions among the hazard, the exposure and the vulnerability.
Drought	Drought is a recurrent feature of climate that is characterized by temporary in precipitation relative to normal conditions, over an extended period of time – a season, a year, or several years. The term is relative, since droughts differ in extent, duration, and intensity.
Water scarcity	Water scarcity refers to the relative shortage of water availability compared to all demands including ecological demands.
Aridity	Permanent climatic condition with very low annual or seasonal precipitation.
Indicators	Indicators are values based on variables representative of drought or another natural or social phenomena..
Uncertainty	Limited knowledge or lack of knowledge to describe the existing state, a future outcome, or more than one possible outcome of drought or another phenomenon.
Forecast	Forecast is the statistical estimate of the definite statement of the occurrence of a future event.
Early warning	Early warning is the provision of timely and effective information, through identified institutions, that allows individuals at risk of a disaster, to take action to avoid or reduce their risk and prepare for effective response.
Preparedness	Preparedness refers to the activities and measures taken in advance to ensure effective response to a potential impact of hazards.
Mitigation	Mitigation is the set of structural and non-structural measures undertaken to limit the adverse impact of hazards
Organisation	A group of persons formally joined together for some common interest.
Institution	A public organization with a particular purpose or function in relation to law, policy, and administration and that establishes rules for its operation.
Network	Network is a group that interacts or engages in informal communication for mutual assistance or support.
Stakeholder	Stakeholders are those actors who are directly or indirectly affected by an issue and who could affect the outcome of a decision making process regarding that issue or are affected by it.

2. DROUGHT HAZARD AND VULNERABILITY CONCEPTS

Vulnerability to drought varies spatially and is determined by natural factors, like the intensity and magnitude of the drought hazard that lead to its susceptibility, and by social factors that lead to exposure, coping capacity and adaptive capacity. The social factors that define vulnerability to drought – for example number of people exposed, per capita water availability, water use trends, technology, policies, etc – change over time, therefore vulnerability also changes. As result, subsequent droughts in the same region will have different effects, even if they are identical in intensity, duration, and spatial coverage, because societal characteristics evolve through time.

A suite of indicators may be used to characterise drought vulnerability. Ideally, the indicator values may define thresholds. Defining critical thresholds is very complex. A threshold is the value at which action is initiated – and not necessarily that at which problems occur. In some literature this leads to two types of threshold – the one is called an action or operational threshold, the other a result threshold.

Vulnerability is a measure of the consequences suffered by a system exposed to a hazard. Under the DEWFORA approach, vulnerability is considered to be a function of susceptibility and coping capacity.

In order to characterize drought vulnerability in the context of drought early warning systems, it is useful to distinguish between two types of indicators: hazard indicators and vulnerability indicators.

Hazard indicators describe nature-based determinants: meteorological, hydrological and agro-ecosystems, and are used to characterize the occurrence of drought. Depending on the focus of the analysis, hazard indicators may be classified in two groups: **diagnostic**, if the emphasis is placed on drought identification and monitoring, and **predictive** if the emphasis is placed on drought early warning. Diagnostic indicators include information relative to the recent past. The spatial and temporal resolution that can be achieved with diagnostic indicators is high and their uncertainty is usually low, since they are mostly based on observations. Predictive indicators are developed to anticipate climatic conditions. They may also be based on recent observations, but they include a modelling component to make predictions about the future. Typically, they are applied over large areas and at low temporal resolution. Their uncertainty is also greater than that of the diagnostic indicators, because they involve uncertain modelling, either of physical or statistical nature, or both. Their early-warning potential is high.

Traditional drought indicators based on the characterization of drought hazard should be extended to consider water uses and users, and estimate the impact of drought on a wider sector of society. The focus on drought vulnerability implies an approach based on the probabilistic characterization of drought impacts. This requires not only a probabilistic characterization of drought occurrence, but also an analysis of the cascading effects of drought on water uses, water users and society as a whole. The goal would be to identify thresholds at which response measures should be applied. The definition of the threshold values should achieve a balance between the frequency of activation of response measures and the effectiveness of the application of the measures. If drought measures are adopted too early, users are frequently confronted with unnecessary restrictions. If the adoption of measures is delayed, it may be too late for them to be effective.

Vulnerability indicators describe social-based responses: anticipation, adaptation and reaction to drought. Vulnerability indicators are essential to implement effective drought early warning system. Their focus is on drought impacts on society. The structure of vulnerability indicators is very diverse, since they have to cover a wide range of impacts across different sectors. In some cases, drought vulnerability indicators are very specific for a given water use and may use simple proxy variables to characterize drought impacts. In other cases they are global, and aim at characterizing the global coping capacity of society in a large region.

The approach proposed has large value from the operational standpoint, since it links the hazard with the propagation of drought effects across water resources, water sectors and society. Nevertheless it is advisable that drought monitoring to concentrate the efforts on the first variables in the time chain in order to anticipate drought impacts. For this reason, diagnostic drought indicators based on precipitation are widely used for drought monitoring. They take advantage of the delay of the socioeconomic response function to drought and allow for the adoption of timely measures early on.

In the context of a drought early warning system, the focus on vulnerability may prove to be very effective since it includes the evaluation of the capacity to anticipate and compensate the adverse effects of drought. If a drought forecast is available, drought managers gain time and can come closer to drought impacts in their analysis. The focus on drought vulnerability requires the development of new drought indicators that are tailor made for a given drought impact. This requires information about the dependency of regional and local communities on water use. In addition to hydro meteorological values, other variables that influence drought impacts can be included in the analysis. This simplifies the difficult task of identifying threshold values of indicators at which drought problems arise.

In the following section, several indicators for drought hazard, vulnerability and adaptive capacity are presented.

3. DROUGHT HAZARD INDICATORS

Drought severity may be characterised according to its intensity, duration, time of onset, and exposure.

Climatic indices are important elements of any monitoring and assessment system because their purpose is to simplify complex interrelationships between many climate and climate-related parameters. Indices make it easier to communicate information about climate anomalies to diverse user audiences and permit scientists to quantitatively assess these anomalies in terms of their intensity, duration, and spatial extent. This allows for the analysis of the historical occurrence of drought and its probability of recurrence, information that is extremely useful for planning and design applications in agriculture and numerous other sectors. An adequate drought index should:

- Provide criteria for declaring the beginning and the end to a drought.
- Represent the concept drought in a particular region.
- Correlate to quantitative drought impacts over different geographical and temporal time scales.

Drought indices are typically single numbers that are calculated including observed and proxy data related to water supply and provide a comprehensible synthesis of a situation for the decision maker that may be more useful than raw data. The use of a particular index to characterize drought depends on the objectives of the analysis and the study region. Most water supply planners find it useful to consult one or more index before making a decision.

Meteorological drought indices respond to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by these indices ends without taking into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts. Meteorological drought indices do not take into account human impacts on the water balance, such as irrigation. Hydrological drought indices take into account water management and streamflow, lake and reservoir levels, and other longer-term hydrologic impacts.

Table 2 summarizes the most commonly used meteorological and hydrological drought indicators. The table also includes a first approximation classification of the values corresponding different levels of drought intensity to be considered only as first approximation thresholds. Local and regional drought analysis must develop specific criteria for drought characterization.

Table 2 Summary of the main meteorological and hydrological drought indices. Source of information: National Drought Mitigation Center, U Nebraska, USA and Ntale and Gan, 2003.

Index	Description and Use	Strengths	Weaknesses
Percent of Normal Precipitation and Accumulated Precipitation Departure	Simple calculation. Used by general audiences.	Effective for comparing a single region or season	Precipitation does not have a normal distribution. Values depend on location and season.
Deciles Gibbs and Maher, 1967	Simple calculation grouping precipitation into deciles. Used by the Australian Drought Watch System.	Accurate statistical measurement. Simple calculation. Provides uniformity in drought classifications.	Accurate calculations require a long climatic data record.
Standardized Precipitation Index (SPI) McKee et al., 1993	Represents the probability of precipitation for any time scale. Used by many drought planners.	Computed for different time scales, may provide early warning of drought and help assess drought severity.	Values based on preliminary data may change. Caution of its application in areas when the precipitation distribution differs greatly from a normal distribution.
Palmer Drought Severity Index (PDSI) Palmer, 1965 Alley, 1984 Palmer Hydrological Drought Index (PHDI) Karl and Knight 1985	Soil moisture algorithm calibrated for relatively homogeneous regions. Used in the USA to trigger drought relief programs and contingency plans. The PHDI is based on moisture inflow (precipitation), outflow, and storage.	The first comprehensive drought index, used widely. Very effective for agricultural drought since includes soil moisture. The PHDI represents surface water supply conditions and includes water management. Simple calculation. Considers reservoir storage and irrigation.	PDSI may lag emerging droughts. Less well suited for mountainous areas of frequent climatic extremes. Complex. Reflects moisture supply in the short term. Since the PHDI considers management, the formulation is unique to each basin or catchment system. Does not take into account the long-term trend.
Crop moisture index (CMI) Palmer, 1968	A PDSI derivative, which reflects moisture supply in the short term across major crop-producing regions	Very effective for agricultural drought since includes soil moisture.	Complex. Reflects moisture supply in the short term. Does not take into account the long-term trend.
Bhalme-Mooley Index (BMI) Bhalme and Mooley, 1979	The BMI models the percentage departure of P from the long-term averages using an algorithm similar to that of	Simpler and easier to compute than PDSI.	Accounts only for precipitation

	the PDSI		
Surface Water Supply Index (SWSI)	Developed from the Palmer Index to take into account the mountain snowpack.	Represents surface water supply conditions and includes water management. Simple calculation. Considers reservoir storage.	Since it considers management, the formulation is unique to each basin or catchment system. May be inaccurate in representing extreme events.
Reclamation Drought Index (RDI) The Bureau of Reclamation	Calculated at the river basin level. Considers temperature, precipitation, snowpack, streamflow, and reservoir levels.	By including a temperature component, it also accounts for evaporation.	Because the index is unique to each river basin, interbasin comparisons are limited.

3.1 DESCRIPTION OF WIDELY USED INDICATORS

Some of the most relevant indices are briefly discussed in the following section. Details on algorithms for index computation may be found in the references or in the Annex.

3.1.1 Precipitation Deciles

Precipitation during a given period of time is grouped into deciles so that, by definition, “much lower than normal” weather cannot occur more often than 20% of the time. The long term precipitation record is divided into tenths of the distribution, each tenth is called a “decile”. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications.

3.1.2 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI, McKee et al. 1993; 1995) assigns a single numeric value to the precipitation which can be compared across regions with markedly different climates. The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. Since precipitation is not normally distributed, a transformation is first applied so that the transformed precipitation values follow a normal distribution. The SPI is designed to be a relatively simple index, based on precipitation alone. Its fundamental strength is that it can be calculated for a variety of time scales, either locally at a given point, or for precipitation averages over different areas. This versatility allows the use of the SPI to monitor short-term water supplies, such as soil moisture, which is important for agricultural production, and longer-term water resources such as ground water supplies, stream flow, and lake and reservoir levels. The ability to examine different time scales also allows droughts to be readily identified and monitored for the duration of the drought.

The SPI can be used as the basis for the analysis of the climatic input. Although the requirement for a transformation to a normal distribution could be a challenge in certain areas with highly skewed precipitation distribution, it offers the advantage of homogeneity across different areas covered by the DEWFORA consortium and can be used as the basis to generate global maps of drought occurrence over the area.

The SPI can be very difficult to calculate in arid climates since the marginal distribution of precipitation is really non-symmetrical. In some regions the number of rainy days with very low precipitation is very high and the number of rainy days with very high precipitation is very low. In order to calculate the SPI it is necessary to find a previous transformation that gives rise to a marginal distribution. For example, in the Tagus Basin the precipitation was transformed calculating the square root of the value. In many cases this can be difficult to implement and it could be an argument to adopt the percentile index. The SPI is normalised, since if transforms the precipitation to a normal distribution, and therefore permits comparison among drought values in different locations.

3.1.3 Surface Water Supply Index (SWSI)

The Surface Water Supply Index (SWSI) has the advantage of combining hydrological and climatic features in a single index and allows for the consideration of reservoir storage. The SWSI is computed for a hydrographic basin or for a water resources system by obtaining the probability of non-exceedance for the values of precipitation, runoff, stored water, and snowpack in the basin (Garen, 1993, Shafer and Dezman, 1982). Each component is assigned a weight depending on local conditions. These weighted components are summed to determine the global SWSI value for the entire basin.

Although the SWSI is not the most widely used drought index, it was selected because of three main advantages. First, it can be computed with relatively few data, which are generally available in most water resources system (rainfall, streamflow, snowpack and reservoir storage). Second, it is computed for a water resources system, and can describe the global behaviour of the entire basin under analysis. Third, the weights assigned to the different components can be adapted to local requirements, depending on the specific structure of a given system (available resources, degree of development, demand type, relative role of regulation, snowpack or groundwater, etc.).

A common feature of all indices is that they are calculated over a particular period of time within the year (e.g., March to October). The period of time to be considered in the calculation depends on the characteristics of the systems to be analysed. For example, dryland agriculture is affected by the atmospheric behaviour of short periods of time (i.e., one or two months) while the rate at which shallow wells, small ponds, and smaller rivers become drier or wetter is affected by the atmospheric behaviour of longer periods (i.e., several months). Some processes have much longer time scales, such as the rate at which major reservoirs, or aquifers, or large natural bodies of water rise and fall, and the time scale of these variations is on the order of several years.

3.2 CHARACTERISATION OF DROUGHT INTENSITY AND EXTENT

3.2.1 Characterisation of drought periods

The characterization of drought periods is a process that has to be tested and evaluated in parallel with the evaluation of impacts. Time series of drought indices should be compared to drought impacts, in order to identify threshold values of the index for every given impact. Depending on local circumstances, indicator threshold values leading to impacts can vary. If the indicators are calibrated appropriately, they have a great potential value for evaluating early warning.

In order to characterize drought and its statistical properties in a particular location or area derived from the selected indices, the following parameters should be considered:

- Duration. Number of consecutive intervals where the variable is below threshold. Occasionally, droughts last for 7 or 8 years, but within that period the severity may fluctuate with spells of rainfall, although still well below average. Other droughts are shorter (one or two years) but more intense with very little rain recorded. In some regions of Africa it is common to encounter decadal drought periods (See Annex 10 for an overview).
- Frequency. Number of drought in a time series. This is linked to the return period of a drought (expected value of the period of recurrence).

- Intensity. Drought intensity is a measure of rainfall deficiency over a period of time. The intensity can be calculated as the ratio between cumulated (sum of the negative deviation throughout the drought duration) deficit and duration.
- Timing and rate of onset. This is important for agricultural systems.
- Extent. It is unlikely that the entire country could suffer drought at the same time. Some droughts can be localised with other relatively close areas receiving normal rainfall.
- Predictability.

3.2.2 Defining intensity and statistical properties

The simple first step is to use the suggested index categories as diagnostic for the drought characterization. For example, the SPI defines severely dry period when the values are -1.5 to -1.99. Nevertheless, this simple approach is not suitable to represent the specific regional droughts characteristics and it does not take into account the threshold of water demand in each case. Annex 4 provides the tables to establish the drought categories. Furthermore, this approach does not take into consideration the other features of drought that are relevant to risk management (i.e., frequency, extent, etc.).

The Run Method characterises objectively drought and its statistical properties. It can be applied both at the local and regional levels. The method provides a structured statistical analysis of the selected drought variable (i.e., precipitation, drought index, or water flow). According to the method, a drought occurs when the selected variable is lower than a selected threshold for that variable, that is a negative run (Yevievich, 1967; Rossi and Cancelliere, 2003). Drought is characterised computing statistical parameters derived from the negative run, such as duration, cumulative deficit, and intensity. The method can be applied considering dependence or independence in the time series of the variable, and it is designed to incorporate simulated variables once the stochastic properties of the basic variable are known.

Below is an step-by-step outline of the method as described by Rossi and Cancelliere, 2003 (Annex 6 provides a more complete description of the method):

1. Selection of the hydrological variable or index.
2. Selection of the time scale (variable aggregation level) considering trade-offs between aggregation and time series length. 2-4 months is usually appropriate.

3. Selection of truncation level based on water demands. Fixed values are used in case of non-periodic time series and seasonally varying thresholds in the case of a stationary period series. This step is critical for the results.

4. Testing for linear trends and randomness.

5. Identify runs (positive and negative) in the time series based on threshold levels. For each negative run (drought) calculate: (a) Duration: number of consecutive intervals where the variable is below the threshold; (b) Cumulated deficit. Sum of the negative deviations throughout the drought duration interval; (c) Intensity of drought. Ratio between cumulated deficit and duration.

6. Summarize the results from 6- by calculating the average, maximum, minimum and total number of droughts.

Rossi, Bonaccorso, and Cancelliere (2004) propose a probabilistic characterization of drought derived from hydrological series to obtain the return-period of droughts with specific intensity, deficit and duration. This methodology could be applied to design storage systems to sustain droughts of a specified duration and maximum deficit, and to evaluate the risk that with the current storage conditions demands during drought of certain characteristics cannot be sustained.

3.2.3 Spatial aggregation

It is recommended to compute area-weighed values of the drought indices calculated from data of the meteorological stations included in the basin or catchment system.

Rossi and Cancelliere (2003) define a way to characterise regional drought based on the selection of an area-based threshold above which a regional drought is consider to occur. Four regional parameters are defined: drought duration, weighed cumulated deficit, drought intensity, and mean area coverage of drought. To compute these regional parameters it is necessary to calculate at each time interval two factors: (a) the area affected by deficit, expressed as a fraction of the total area and ranging between 0 and 1; and (b) the area deficit, which provides insight on the total amount of deficit in the area, calculated as the sum of deficits at each site weighed by the influence area at each site. The influence area at each site is calculated by spatial interpolation. Garrote et al. (2003) have applied a similar methodology in the Tagus River Basin.

4. INDICATORS OF DROUGHT IMPACT

For designing an early warning system it is important to understand the main impacts or susceptibilities of drought in the basin. The relevant drought impacts considered for each river basin may be characterized, such as impacts in the hydrology, the agriculture or other economic sectors and impacts in the environment. Contrary to drought hazard indicators, there is very little literature on drought indicators focusing on susceptibility or impacts. Susceptibility or impact indicators are linked to a specific water sector, and cannot be applied at regional or large scales, so it is very difficult to identify widely applicable ones. They are specifically tailored to evaluate the impacts of drought in a given sector. In many occasions, they use proxy variables that are related to economic impacts. In this section, we present a methodology to define impact indicators in rain fed agriculture and in regulated water supply systems.

4.1 IMPACT INDICATORS IN RAIN FED AGRICULTURE

The main proxy of drought impacts on rain fed agricultural systems is crop production. In order to characterise the sensitivity of agricultural response it may be useful to consider the quantification of some aspects of agricultural production, such as:

- Identification of the agricultural system(s) representative of the river basin or water catchment system. For example, subsistence farmers in dryland areas, commercial irrigated farms, etc.
- Definition of the variables that characterise each agricultural system. For example, crop yield, water demand, etc.
- Definition of causal relationships between the agricultural variables and drought. In order to establish the drought risk in the agricultural sector, it is essential to provide solid evidence based on as much quantitative information as possible to place confidence in these relationships.

Crop models can be a useful analytical tool to establish quantitative relationships between climatic input and crop production. Many authors have developed statistical models of productivity responses to variations in input variables and they are widely used to investigate the effect of climate fluctuations on crop yield as well as their temporal and spatial variation. With the help of these models, the time series of meteorological variables (typically temperature and precipitation) are used to compute a time series of crop yield. Since interannual temperature fluctuations are smaller than those of precipitation, the crop models may be run with average climatic temperatures and actual precipitation. The analysis of the variability of the resulting series may produce a probability density function of crop yield that can be used to infer a probabilistic indicator of crop productivity. An important focus of this analysis should be the timing of moisture deficit during the growing season, since impacts may be very variable, as is shown in Figure 1.

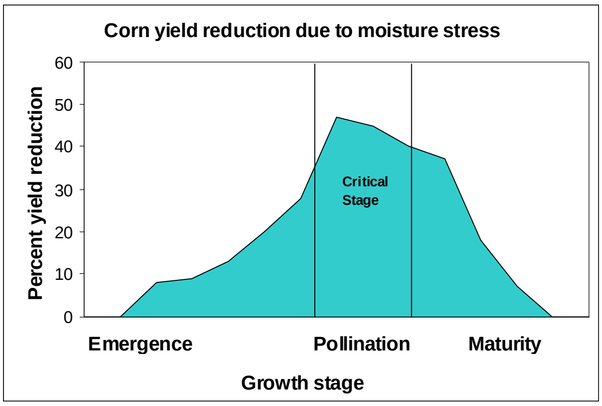

Figure 1 Effect of moisture deficit on yield reduction during the growing season.

If crop models are not available for the region, statistical analysis of the correlations of drought indices with the relevant variables that define the system can be made. This step is essential for the selection and validation of the drought indices as thresholds of the drought risk. The indices that show a larger significant correlation with the impacted variables should be the ones to consider as potential triggers to activate drought response measures.

In many complex systems there may be several relevant impacts. In this case, an aggregated measure of sensitivity of the agricultural system to drought can be defined based in the combination of the partial impacts. The aggregated measure may be constructed by normalizing and scaling the proxy variables with respect to some common baseline.

In the absence of analytical data, a quantitative estimation of drought susceptibility of agricultural systems can be made based on surveys. Some agricultural variables that may be affected by drought and that can be characterised in a survey include: farm income, costs, access to water for irrigation, water quality, crop productivity, animal welfare, etc.

4.2 IMPACT INDICATORS ON REGULATED WATER SUPPLY SYSTEMS

In many systems, water is delivered to users through an organized water supply system. In these systems, hydraulic infrastructure and management strategies are applied to compensate for the spatio-temporal irregularities of the hydrologic cycle, so that water is timely supplied under normal conditions. During droughts, lack of water can mean inadequate supply to some demands, causing water shortages.

Impact indicators in water supply systems are directly related with the probability of occurrence of water shortages, which differ from droughts because they are related to water demands. Shortages result from a temporal unbalance between water supply and demand. They are usually originated by a meteorological phenomenon, but are also conditioned by other time-varying factors, such as demand development, supply infrastructure and management strategies. The result of the unbalance is demand deficit, which is of concern for water managers, and is therefore used as a proxy for drought impacts in regulated water supply systems.

Drought impact indicators are defined by computing the probability of occurrence of deficits through risk analysis. The following magnitudes are of interest:

- Probability of failure occurrence (probability of not satisfying the demand)
- Severity of failures (magnitude of the deficit)
- Failure duration (time span when deficits occur)
- Economic impact of failures

The probability distribution of deficits depends on demand characteristics, available water resources and infrastructure. Water resources systems models are used to characterize the probability of deficits under different conditions. During the planning stage, risk analysis is used to quantify and compare the risk of failure associated to different management alternatives in the long term (several decades). This activity is called unconditional risk analysis, since the state of the system at the beginning of the analysis does not influence model results. During the operational stage risk analysis is used to quantify and compare the risk associated to different management alternatives in the short term (a few months). This activity is called conditional risk analysis, since the results obtained are highly dependent on the initial condition of the system.

The value that best describes the state of a water supply system in conditional risk analysis is the amount of water stored in the reservoirs. Whenever the development of a meteorological drought is being discussed, water managers check for stored water in the reservoirs in order to decide whether there is a significant risk of water deficit. Therefore, water storage in reservoirs is a suitable variable to define drought indicators focused on impacts. Indices linked to reservoir storage comply with most of the requirements proposed by (Steinman et al., 05) for drought indicators and triggers and are ideal for decision making, because they can be interpreted in terms of risk of failure of the systems.

The proposed methodology for the definition of drought impact indicators is based on the identification of thresholds to activate drought response measures (Garrote et al., 2006). Since future reservoir inflows are uncertain, the drought impact indicator should be formulated in probabilistic terms. The drought impact indicator for any given system state may be defined as the probability of satisfying a fraction, *"f"*, of the demand in a time horizon, *"h"*. Values of *f* and *h* are model parameters that are specific of every system. They depend on several factors: the type of the demand in the system (urban, irrigation, hydropower, etc.), the reliability of the current water supply system, the alternative management strategies that can be applied during droughts, the vulnerability of the demand to deficits of a certain magnitude, etc. Typically, higher values of *f* and *h* should be used for urban water supply demands than for irrigation demands. Thresholds to activate drought response measures are critical values of the probability *"p"*, meaning that managers should act when they believe that the probability of not satisfying the required fraction of the demand is too high.

The indicator may be easily computed by obtaining for every month the probability of satisfying the fraction *f* of the demand in the time horizon *h* as a function of reservoir storage, *"S"*, in the system.

Figure 2 shows as an example the result of the analysis for an urban water supply system to a large city. Each line corresponds to the relationship between system storage and the probability of satisfying 100% of the demand during one year for every month. The drought impact indicator is obtained for every month in the time series by computing the probability that corresponds to the observed storage value. Figure 3 represents the time evolution of storage in a simulation and the corresponding values of the drought impact indicator. Since it is an urban water supply system, the reliability is very high and there is only one situation where the probability of having a deficit is significant.

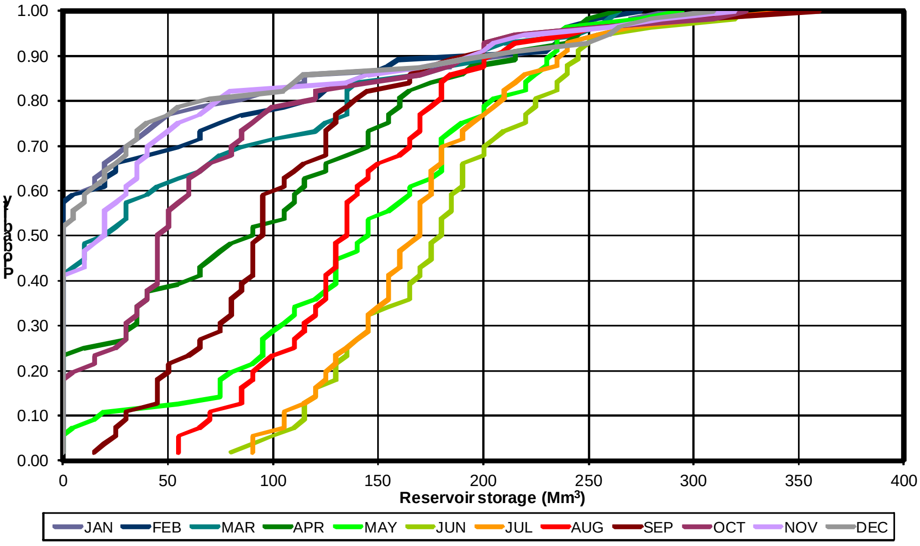

Figure 2 Probability of satisfying 100% of the demand during one year as a function of reservoir storage in an urban water supply system

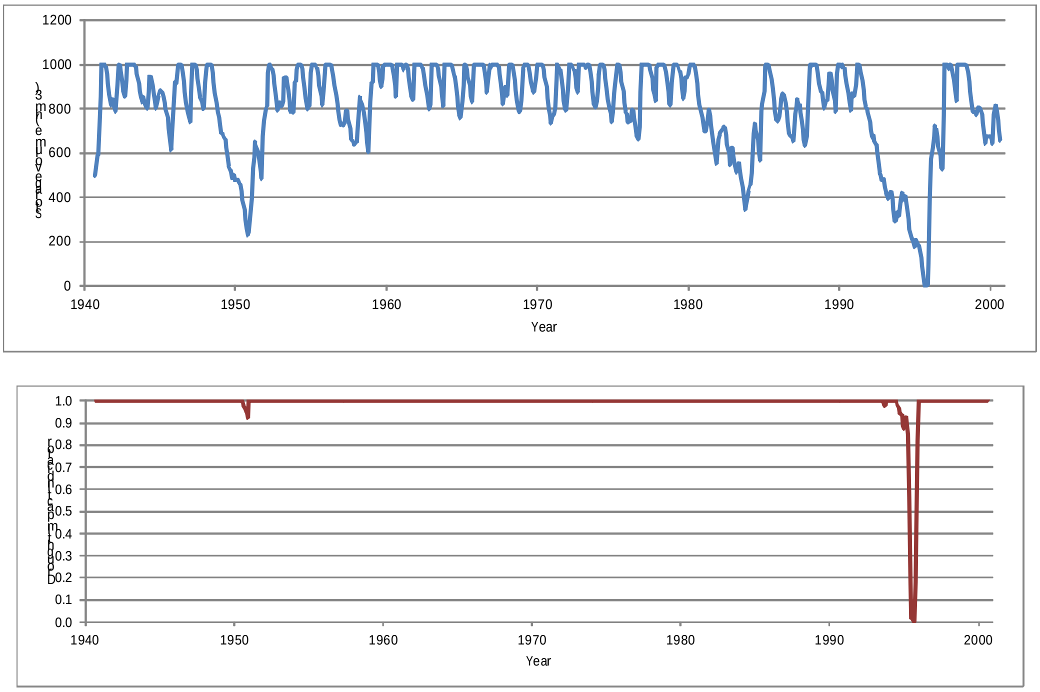

Figure 3 Time evolution of reservoir storage (above) and the corresponding drought impact indicator.

The above methodology, or some variation, may be used in any complex system where both a model and data are available to make the probabilistic analysis through Monte Carlo simulation. In particular, it may be used to address systems that depend on groundwater (substituting reservoir storage by piezometric head) or by study ecosystems linked to water resources (substituting demand deficit by ecosystem damage). If information is available, the analysis may be pushed further to include also estimation of economic damages.

However, the availability of data and models is not usual in all basins. In the case there is not enough information to apply the methodology, a simple approach may include the following indicators:

- Water demand / Average inflows. Provides information about the degree of development of water resources in the system. Ratios close to 1 mean large impacts of droughts, because there will be frequent system failures, depending on interannual or seasonal variability of hydrologic series.
- Statistical measures of variability of water inflows. They have to be derived from the distribution function that better fits historical inflows of the system, such as correlations, standard deviation, skewness, coefficient of variation, consecutive low flows, etc. This provides basic information on the risk levels that the system is supporting by assigning probability levels to a given scenario.
- Water demand / Reservoir capacity. Provides information about the quantity that the system is able to supply from storage.
- Reservoir capacity / Average inflows. Provides information on the capacity of the system to overcome inflow irregularities (droughts).
- Annual water demand / Current reservoir storage. Represents the expected time to failure, in years, if future inflows are neglected. Provides information on the margin of operation of the system.

5. INDICATORS OF ADAPTIVE CAPACITY

5.1 COMPONENTS OF ADAPTIVE CAPACITY

The capacity to adapt to drought or other hazards is implicit in the concept of sustainable development and implies economic as well as natural resource components. Adaptive capacity explains the system's capacity to anticipate, cope, and recover from drought. While the sensitivity clearly depends on the intensity of drought, the response has – potentially – many social, human and environmental dimensions. Therefore the adaptive capacity is difficult to measure and has to be represented by a combination of several variables. Crucial determinants of adaptive capacity are water policies and the projections of economic growth (Iglesias et al., 2007; Iglesias et a., 2011). The ACI may be used to understand the vulnerability of a system to drought and therefore assist in the definition of early warning systems.

Here we present a methodology to estimate an indicator of adaptive capacity to drought (ACI) focusing on socioeconomic, natural and technological variables, and on their role in modifying drought impacts, especially for agricultural production and water resources.

The ACI evaluates the intrinsic characteristics of a certain system that define its response to drought. The ACI includes with five major components that characterize the social capacity, economic capacity, technological eco-efficiency and natural capital. There are two key challenges in the design of a ACI that is an adequate representation of the cause-effects relationship between drought and its impacts. First, the selection of the variables to be included in the ACI and second the weighting of each variable- These two questions are ideally answered in the context of decision-oriented stakeholder and expert dialogues. Here we present a ACI that includes a very large set of important variables from the theoretical point of view. The stakeholders in the case studies should select the most adequate variables and their weighting in each case.

Social capacity. Social characteristics depend to a large extent on the type of policies implemented in the country or region, ranging from self-sufficiency strategies based on market or protective policies for industrialized nations where agriculture might only play a marginal role. This component can be represented through some general variables like agricultural employment, which has a negative correlation to the overall adaptive capacity because it implies a greater dependency of society on a highly variable sector. Other variables associated to this component are literacy rate, life expectancy or access to sanitized water, all of them positively correlated to adaptive capacity because they imply healthier and stronger societies that can develop and implement solutions to adapt to drought in a more efficient manner. The evaluation of the effectiveness of institutional interaction and response are determinant for the implementation of potential adaptive capacity to drought.

Economic capacity. As in the previous case, the level of economic development is a variable of the capacity of a system to make investments in development technologies, food security and income stabilization. The variable selected for this component is GDP, that is has a positive correlation to adaptive capacity, while the rate of agricultural GDP shows a higher dependence on agriculture and, again, a lower adaptive capacity.

Technological eco-efficiency. Eco-efficiency increases significantly the adaptation potential of a system. The indicators selected include GDP per unit energy use, high technology exports and CO2 emissions per capita. The development of agriculture significantly decreases the dependency of this sector on climatic variables and stabilizes production and this evolution is driven both by policies that aim for more productive crops or by private initiatives to increase the revenue from agriculture. The indicators selected for this component represent the technological advancements applied to agricultural production. Therefore these indicators have a positive correlation with the overall adaptive capacity index, as they indicate the level of independence from climatic variables.

Natural capital. One of the most relevant threats imposed by drought is related to the water resource system resulting in increased water scarcity. Adequate drought early warning systems depend on the reliability and vulnerability of water resource systems to confront water scarcity.

Water management is related to climatic conditions, but it also depends on other factors, such as infrastructure for water storage or transport, excess of demands or their mutual incompatibility, and constraints for water management (determined by policies). Policies related to the management of natural resources are crucial to develop early warning strategies. This component needs to incorporate information related to the variability of precipitation, which decreases the general adaptation capacity of a system because of little effectiveness of developed infrastructure. In the case of agricultural systems, adaptive capacity also needs to include some variables related to the use of water in this sector, such as agricultural water use or irrigated area. These two variables show a positive correlation with the adaptive capacity because the more water is used for agriculture; the easier it is to stabilize agricultural production independently from annual precipitation or distribution.

5.2 COMPUTING THE ADAPTIVE CAPACITY INDICATOR

The methodology is appropriate to integrate both quantitative and qualitative characterisations of adaptive capacity -- this permits the involvement of the stakeholders in the process. The ACI can be applied locally or spatially and with different aggregation levels of the input data. The intermediate components can be evaluated independently, allowing comprehensive interpretation of the strengths and weaknesses of each system.

The sequential steps taken for the quantification of the ACI are: (a) select variables that are important; (b) normalize the variable values with respect to some common baseline; (c) combine the sub-component variables within each category by weighted averages; and (d) quantify climate ACI as the weighted average of the components. The scores of the climate ACI range on a scale of 0 to 1, with the total being generated as the average of each component.

The approach is flexible and can be applied to managed and natural ecosystems as well as to socio-economic systems. The methodology is appropriate to integrate both quantitative and qualitative characterisations of adaptive capacity -- this permits the involvement of the stakeholders in the process. The index can be applied locally or spatially and with different aggregation levels of the input data. The intermediate components can be evaluated independently, allowing comprehensive interpretation of the strengths and weaknesses of each system.

5.2.1 Selection of the variables to be included

Table 3 shows the components of the ACI and Table 4 summarises the sources of data and the units of measurement.

Table 3 Components of the ACI, aspect relevant to adaptive capacity and suggested variables to be discussed with the stakeholders in each case study

Components	Aspect relevant to adaptive capacity	Variables
Social capacity	Human development (individual level)	Adult literacy rate
		Life expectancy
	Collective capacity	Agricultural GDP
		Population without access to improved water
		Population below the poverty line
	Institutional coordination	Institutional relations
		Public participation
	Pressure on resources	Total population
Economic capacity	Economic welfare	GDP per capita
		Energy use
	Public intervention	Public expenditure
Technological eco-efficiency	Eco-efficiency	GDP per unit energy use
		High technology exports
		CO2 emissions per capita
	Agricultural innovation	Agricultural machinery
		Fertilizer consumption
Natural capital	Water management	Total water use
		Agricultural water use
		Irrigated area
	Environmental damage	Area salinised by irrigation

Table 4 ACI variables, sources of data and units of measurement

Variables	Source of data	Units
Adult literacy rate	UN, Human Development Index	Percentage of population 15 years or older which is literate
Life expectancy	UN, Human Development Index	Total years of live expectancy at birth
Agricultural GDP	FAO	Percentage of total GDP
Population without access to improved water	FAO, Aquastat	Percentage of total population
Population below the poverty line	UN, Human Development Index	Percentage of population
Institutional relations	WP2	Index (0 to 5) based on institutional analysis
Public participation	WP2	Index (0 to 5) based on institutional analysis
Total population	UN, Human Development Index	Number of people
GDP per capita	World Bank	Current 2004 US$
Public expenditure	Eurostat (for the EU countries); OECD (for North African countries)	Millions of €
Energy use	World Bank	10^6 kg of total oil equivalent
GDP per unit energy use	World Bank	2000 PPP US$ per kg of oil equivalent
High technology exports	World Bank	Percentage of manufactured exports
Agricultural machinery	FAO	Number of tractors per 100 ha of arable land
Fertilizer consumption	FAO	kg of N-fertiliser per ha of arable land
Total water use	FAO, Aquastat	10^9 m3 per year
Agricultural water use	FAO, Aquastat	10^9 m3 per year
Irrigated area	FAO, Aquastat	Percentage of cropland irrigated
Area salinised by irrigation	FAO, Aquastat;	Percentage of cropland
Precipitation	FAO, Aquastat; CRU	Total annual precipitation mm/year

5.2.2 Normalization to some common baseline

In order to compare across case studies or in the Africa-wide analysis, the variables shown in Table 3 should then be normalised between the different case studies in order to compare the results. The standardization may be made with respect the maximum value of each indicator across the areas to combine within the categories and guarantee that the ACI is a percent rate. Combine the sub-component variables within each category by using a weighted mean with weights inversely proportional to the impact uncertainty level.

We propose to consider the weights separately for each of the category in order to evaluate them independently, noting the strengths and weaknesses of each component of the total ACI in each case study or country.

5.2.3 Quantification of the ACI

The ACI here is calculated with a similar methodology as the Human Development Indicator (HDI). Each component of the ACI can be viewed as a dimension. Before calculating the overall ACI, an indicator for each of the dimensions needs to be computed. To compute the dimension indicators, minimum and maximum values are chosen for each underlying variable. These minimum and maximum values are used to harmonize the ACI and refer to the minima and maxima of the areas which are the in the scope of analyzes. For all values, except literacy rate and life expectancy, the minima and maxima among the nations are used as a harmonization basis. For life expectancy and literacy rate, the goalposts from UNDP (2010) are applied. Performance in each dimension is then calculated as the dimension indicator with

$$\frac{x_i - x_{min}}{x_{max} - x_{min}}$$

for proxies which exhibit a positive correlation to the overall adaptive capacity, and with

$$1 - \left(\frac{x_i - x_{min}}{x_{max} - x_{min}}\right)$$

for proxies which exhibit a negative correlation.

$x_i =$ proxy value for country in question, $x_{\min} =$ minimum of the values in the sample, and $x_{\max} =$ maximum of the values in the sample..

The overall adaptive capacity index is then calculated as a weighted arithmetic mean of the dimension indices and gives the relative adaptive capacity of a country in respect to the given countries.

5.3 POLICY RELEVANCE OF THE SELECTED VARIABLES

The variables selected include adult literacy, life expectancy at birth, population without access to improved water, and GDP, that are among the most favoured indicators of sustainable development, and are used as components of United Nations Development Programme's (UNDP) Human Development Index. The relevance of those and other indicators selected is presented below.

- Adult literacy rate. The proportion of the adult population aged 15 years and over which is literate (UN, 2008). Measured as a percentage. This driving force indicator responds to the need of promoting education, public awareness and training, a goal in any sustainable development program. Literacy is critical for promoting and communicating drought policy and improving the capacity of people to address drought impacts. It provides skills for effective public participation in decision making.
- Life expectancy at birth. The average number of years that a newborn could expect to live, if he or she were to pass through life subject to the age-specific death rates of a given period (UN, 2008). It is measured in years of life expectancy at birth. This state indicator is closely connected with health conditions and determines the potential of the population for future development and growth, which in turn reflects gains in public awareness of environmental problems and public participation.
- Population without access to improved water. Proportion of population without access to an adequate amount of safe drinking water in a dwelling or located within a convenient distance from the user's dwelling (FAO, 2008). It is measured in percentage of total population. This state indicator is a primary element of health care of fundamental significance to the state of sanitation and the increase the risk and frequency of major diseases relevant to drought.
- Population below the poverty line. The proportion of population living below the poverty line, measured as total expenditure on all goods and services consumed per person and year. The poverty line adopts a different value in each country according to the development level to reflect the necessary income to attain a basic consumption and health care needs. Poverty comparisons are required for an overall assessment of human welfare and a country's progress in poverty alleviation and/or the evaluation of specific policies or projects. This state indicator reveals a number of aspects of vulnerability reduction policies in the context of drought, such as the regional or sectoral priorities for public spending to minimise impacts. The increase of poverty under drought conditions remains a major challenge for vulnerability reduction policies.

- Institutional relations. Relations among programs, norms, and legislature related to resources management, with an emphasis on water scarcity management and drought. It is an indication of the interest of a country to incorporate drought policy into the environmental and economic concerns. Such accounts facilitate better integration among national and local governments, industry, science, interest groups, and the public in the process of developing effective approaches to reduce vulnerability to drought. This response indicator is estimated as an index from 0 to 5 evaluated by different stakeholders groups representing government, non-governmental organizations (NGOs), academia, business and media.
- Public participation. Public participation evaluates the representation of major groups in National Councils for resources management. This response indicator is estimated as an index from 0 to 5 evaluated by different stakeholders groups representing government, non-governmental organizations (NGOs), academia, business and media. The indicator identifies the involvement of major groups in institutional mechanisms that have been created at the national level for the development and implementation of drought policies. The genuine involvement and participation of all social groups in decision making is critical to the achievement and implementation of effective early warning systems. The information provided by this indicator may be limited as it does not necessarily reflect the effectiveness of the participation of major groups in the process of policy making within national councils. There may be other channels through which major groups can participate in decision making related to drought. The results may vary considerable among countries.
- Total population. The total population size in a specified year. This state indicator identifies one of the crucial elements affecting vulnerability to drought and is a fundamental indicator for national decision makers with economic, social, and environmental significance.
- GDP per capita. Gross domestic product (GDP) per capita is obtained by dividing annual or period GDP at current market prices by total population. It is measured in monetary units (the data of the World Bank which was used is measured GDP in US$). This driving force indicator is a basic economic growth indicator that measures the level of total economic output. It reflects changes in total production of goods and services. The indicator measures the economic capacity to respond to climate risks.
- Energy use. The total consumption of fossil fuel in the country, measured in kg of oil equivalent. Traditionally, energy consumption is a key aspect of economic development, but it is recognised that it has major impacts on the environment and drought.

- GDP per unit energy use.GDP per unit of energy use is an indicator of the energy efficiency of a nation's economy. It is calculated as units of GDP per unit of energy used. The higher the value of the indicator, the more energy efficient the economy is.
- Public expenditure. Net expenditure by a country in a given year measured in millions of €. This driving force indicator measures the public intervention in the economy and is related to the investment measures that stimulate adoption of drought policies. It is an important element of the process of vulnerability reduction, especially in areas with limited infrastructure. However, there are limitations on the use of this indicator due to differential effectiveness of public expenditures (for example arising from corruption).
- Fertiliser consumption. The extent of nitrogen fertilizer use in agriculture per unit of arable land area. It is measured in kg of N-fertilizer per hectare of arable land. This driving force indicator measures the intensity of fertilizer use, which is an indicator of agricultural technology. Very high values of this indicator may also show the potential environmental pressure from agricultural activities. Nevertheless, when comparing countries with different levels of development, N-fertiliser use is linked to agricultural technology.
- Total water use. The total annual water use is measured in volume of water used per year. This driving force indicator shows the degree to which available water resources are being used to meet the country's water demands. It is an important measure of a country's vulnerability to water shortages, a main issue in relation to drought. The indicator can reflect the extent of water resource scarcity with increasing competition and conflict between different water uses and users.
- Agricultural water use. The agricultural water use measured in volume is an indicator related to the management potential of the system.
- Irrigated area. Irrigated area is measured as a percentage of total cropland. This driving force indicator shows the degree of importance of irrigation within the country's agricultural sector, from the point of view of water and land resource utilization. This indicator shows to what extent arable land and water resources are already used in an intensive manner. It can indicate level of conversion of land to high input agriculture. Irrigation is linked to other intensification processes with potentially negative effects on sustainability. These negative effects are captured in the indicator "area salinised by irrigation" also used in this evaluation.
- Area salinised by irrigation. The area affected by salinization measured as a percentage of total agricultural area, is a state indicator that shows the degree of productive land loss, decreasing production, and associated water-born diseases that result from non-

sustainable irrigation water management. This indicator is highly significant to determine degradation of land resources. It limits the possible adaptation actions to drought.

6. PROPOSAL FOR EVALUATING VULNERABILITY IN THE CASE STUDIES

This section of the report provides some guidelines on how to evaluate drought vulnerability in the case studies, based on a low chart that outlines the steps of the analysis. Each of the components of the flow chart are then discussed in the following sub-sections and finally a proposal of indicators to be included in each case study is provided.

6.1 PROPOSAL FOR EVALUATING VULNERABILITY

In the previous sections we have presented a suite of indicators may be used to characterise drought vulnerability that characterise the natural and social aspects. Ideally, the sets of indicator values may define vulnerability thresholds. Defining critical thresholds is very complex. A threshold is the value at which action is initiated – and not necessarily that at which problems occur. In some literature this leads to two types of threshold – the one is called an action or operational threshold, the other a result threshold. Figure 4 outlines a simple proposal to define vulnerability levels based in the quantification of hazard and adaptive capacity indicators.

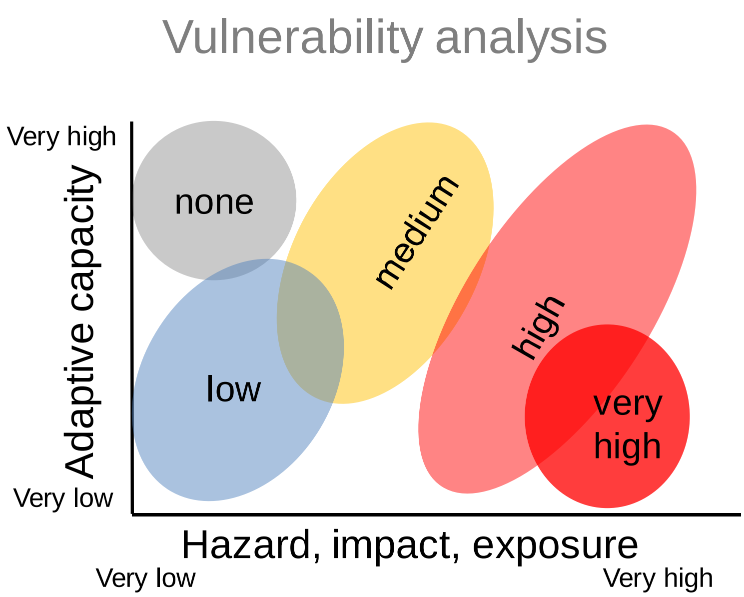

Figure 4 Proposed definition of vulnerability levels

In practice, the steps that that may be considered in the analysis include: Define hazard (meteorological or hydrological); Define the impacts in agriculture, water, ecosystems, health, etc; Define exposure (number of people affected); and Define coping capacity or adaptive capacity (Figure 5).

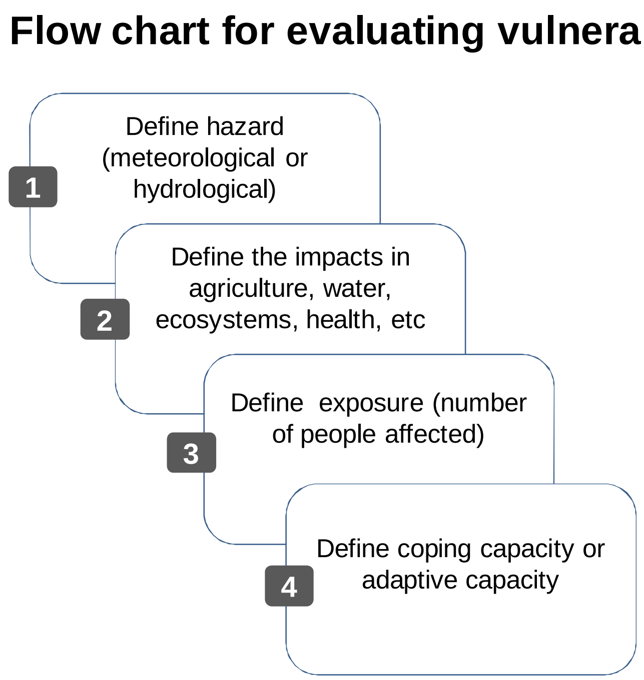

Figure 5 Flow chart for evaluating vulnerability

6.2 DEFINITION OF HAZARD

The methodology is described in Section 3. For practical applications, the selection of drought indicators may include the following criteria:

- Require only existing and readily available data;
- Be easy and cheap to apply;
- Be appropriate to represent the particular rainfall and streamflow conditions in the area under consideration;
- Discriminate to a reasonable degree between different levels of intensity; and
- Be valid, the results being reasonable predictors of the results of more detailed studies.

Based on the characteristics of the indices and their relative strengths and weaknesses, the general data availability and the characteristics of the agricultural and water supply systems, we suggest the use of three basic indices: Precipitation deciles, Standard Precipitation Index (SPI), and Surface Water Supply Index (SWSI). These three indices will then be used to characterise drought and for attribution of the drought effects to specific vulnerable systems. If possible, the indicators should be calculated over a time period to evaluate the dynamics of drought.

6.3 DEFINITION OF IMPACTS

The methodology is described in Section 4. Statistical databases may be used to evaluate impacts. In case the information is not available, consultation with stakeholders may provide qualitative results.

6.4 DEFINITION OF EXPOSURE

The definition of the number of people affected by drought in each case is extremely valuable for estimating overall vulnerability. The sources of data vary in each case study.

6.5 DEFINITION OF ADAPTIVE CAPACITY

The ACI evaluates the intrinsic characteristics of a certain system that define its response to drought. The ACI includes with five major components that characterize the social capacity, economic capacity, technological eco-efficiency and natural capital. There are two key challenges in the design of a ACI that is an adequate representation of the cause-effects relationship between drought and its impacts. First, the selection of the variables to be included in the ACI and second the weighting of each variable- These two questions are ideally answered in the context of decision-oriented stakeholder and expert dialogues. Here we present a ACI that includes a very large set of important variables from the theoretical point of view. The stakeholders in the case studies should select the most adequate variables and their weighting in each case.

6.6 PROPOSED INDICATORS IN THE CASE STUDIES

Table 5 summarises the suggested indicators in the case studies based on the objectives and the tools and models available in Dewfora.

Table 5 Summary of the suggested indicators in the case studies based on the objectives and the tools and models available in Dewfora

Case study	Focus of the early warning	Suggested indicators
Oum-er-Rbia Basin	Agriculture Strategic importance providing water to irrigated and rain-fed agriculture, mining, large manufacturing industries, and water transfers to large cities, including Casablanca and Marrakech. Optimisation of water release to irrigators and analyze the effectiveness of adapted agricultural practices on vulnerability. Optimisation of crop management to dryland, early warning doe insurance Committee that takes decisions on drought	Streamflow, crop yield, rainfall, adaptive capacity, exposure
Niger River basin	Wetlands Encompasses nine countries, about 30% of the basin is located in Mali, one of the poorest countries in the world where agriculture is a main economic activity that depends on the onset and intensity of the annual monsoon Application of a mesoscale distributed eco-hydrological model combining hydrology, vegetation and agriculture. Pilot the drought preparedness by predicting future hydrological and agricultural drought risk through climate projections. Wetlands in the inner Niger delta.	Precipitation, streamflow, reservoir operation, state of ecosystems, adaptive capacity, esposure
Limpopo Basin	Institutional Only source of water for millions of people, shared basin Improve the flow of information Mental model Regional analysis because the shared basin has sto have a good coordination strucuture To give the gap analysis, to look into the institutional set-up Provide recommendations for improving institutional structure Include several types of end-users and analyze how the issued warnings flow through the institutional structure	Precipitation, streamflow, crop yields, management rules, institutional response, adaptive capacity, exposure
Eastern Nile Basin	Water Only source of water for millions of people Water allocation is a controversial issue and cause of tensions between the countries, analyse Blue Nile and Atbara Basins	Hydrological indicators, adaptive capacity, exposure
Pan-African	Value of the forecast Develop and test a pre-operational system for drought monitoring and forecasting in Africa at the continental scale, using medium-range, monthly and seasonal probabilistic forecasts Extreme forecast indices Development and implementation of the African drought map server	Extreme forecast indices, Precipitation, SPI

7. ANNEX. INDICES FOR CHARACTERISATION OF THE DROUGHT HAZARD

This Annex shows how to calculate the most common drought indices. Additional sources of information include:

Hayes, M.J. (2004) Drought Indices, National Drought Mitigation Center. http://drought.unl.edu/whatis/indices.htm.

Vicente-Serrano S.M., Santiago Beguería, Juan I. López-Moreno (2010) A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index - SPEI. Journal of Climate DOI: 10.1175/2009JCLI2909.1

7.1 PERCENT OF NORMAL PRECIPITATION

The Percent of Normal Precipitation is the percent value of normal precipitation that represents the actual precipitation during a particular time period.

$PNP_i = (AP_i/NP_i)*100$

Where,

i: Time period of calculation (i.e., a month, a season, a year)

PNP: Percent of normal precipitation

AP: Actual precipitation

NP: Normal precipitation, typically considered to be a 30-year mean. Normal precipitation for a specific location is considered to be 100%.

7.2 ACCUMULATED PRECIPITATION DEPARTURE

Accumulated precipitation departure is the percent change of accumulated precipitation departure in relation to the long-term average.

APDi = ((APi - AvgPi) / AvgPi) * 100

Where:

i: time period

APi: Accumulated precipitation is the total precipitation that has fallen during a number of months (i).

(APi - AvgPi): Accumulated precipitation departure is then the amount by which the indicated accumulated precipitation is above or below the long term average for exactly the same set of months. The local seasonal cycle of long-term average precipitation is automatically accounted for. A departure of 0 indicates totals are exactly equal to climatological values.

APDi: Percent accumulated precipitation departure for the same time.

7.3 DECILES

Precipitation during a given period of time is grouped into deciles so that, by definition, “much lower than normal” weather cannot occur more often than 20% of the time. Table 1 shows classification of drought conditions according to deciles.

The long term precipitation record is divided into tenths of the distribution, each tenth is called a “decile”. The first decile is the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications.

Table 6 Classification of drought conditions according to deciles.

Decile Classifications	
deciles 1-2: lowest 20%	much below normal
deciles 3-4: next lowest 20%	below normal
deciles 5-6: middle 20%	near normal
deciles 7-8: next highest 20%	above normal

deciles 9-10: highest 20%	much above normal

The decile method was selected as the meteorological measurement of drought within the Australian Drought Watch System because it is relatively simple to calculate and requires less data and fewer assumptions than the Palmer Drought Severity Index (Smith et al., 1993). Farmers in Australia can request government assistance if the drought is shown to be an event that occurs only once in 20–25 years (deciles 1 and 2 over a 100-year record) and has lasted longer than 12 months (White and O'Meagher, 1995).

7.4 PALMER DROUGHT SEVERITY INDEX (PDSI)

The Palmer Drought Severity Index (Palmer, 1965) measures the departure of the moisture supply. The concept is based on the supply-and-demand concept of the water balance equation, taking into account more than just the precipitation deficit at specific locations. The index provides measurements of standardised moisture conditions so that comparisons using the index can be made between locations and between months.

The PDSI is calculated based on precipitation and temperature data, as well as the local Available Water Content (AWC) of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. Complete descriptions of the equations can be found in the original study by Palmer (1965) and in the more recent analysis by Alley (1984) and operational modifications by Heddinghaus and Sabol (1991).

A long-term archive of the monthly PDSI values for every climate division in the United States exists with the National Climatic Data Center from 1895 through the present. Weekly Palmer Index values are calculated for the climate divisions during every growing season and are available in the Weekly Weather and Crop Bulletin. All values are available at the Climate Prediction Center at http://www.cpc.ncep.noaa.gov/products/.

The method of calculation includes the following steps:

Input Data: Temperature, Precipitation, Normal Temperatures, Latitude, and Available Water Holding Capacity (AWC) of the soil.

Calculate Potential and Actual Values for the following variables of the water balance equation: Evapotranspiration (E), Recharge (R), Runoff (RO), and Loss (L).

Calculate the Moisture Departure, d for each period as the difference between actual monthly precipitation (P) and "Climatologically Appropriate Rainfall" ($\hat{P}$).

$$d = P - (\alpha_i PE + \beta_i PR + \gamma_i PRO - \delta_i PL). \quad (3)$$

PE is potential evapotranspiration, PR potential water recharge to soil, and PRO potential runoff. PL is the "potential loss of soil water to evapotranspiration" . PL is defined as the sum of soil water available for evapotranspiration from the two layers defined in the soil model: the surface layer and the underlying layer.

The four water-balance coefficients in Equation (3) α, β, γ, and δ, are long-term averages of the ratio of the potential values previously calculated to its actual value

$$\alpha_i = \overline{ET_i}/\overline{PE_i}, \quad \beta_i = \overline{R_i}/\overline{PR_i}, \quad \gamma_i = \overline{RO_i}/\overline{PRO_i}, \quad \delta_i = \overline{L_i}/\overline{PL_i}, \quad (4)$$

Calculate the Moisture Anomaly, z, for each period.

The Moisture Anomaly, z, is calculated by multiplying the Moisture Departure, d, by the Climate Characteristic k.

$$Z_i = (Kd)_i, \quad (2)$$

K (Climatic Characteristic) is a coefficient dependent on location, time of the year, PET, R, RO, P and L among other factors which are important when calculating the calibrated PDSI.

Calibration

This step is skipped in the calculation of the original PDSI. To calibrate the PDSI, values of the duration factors and the climate characteristic must be determined.

Calculate the PDSI values

$$PDSI_i = 0.897\, PDSI_{i-1} + \frac{1}{3} Z_i.$$

Subscripts i and i - 1 indicate current and previous months at some arbitrary time, respectively, and PDSI0 = 0.

The values of 0.897 and (1/3) are empirical constants that Palmer derived using data from two climate divisions. The PDSI values are calculated iteratively using the Z-index and the duration factors.

$$PDSI_i = \sum_{m=0}^{i} \frac{c^m}{3} Z_{i-m}. \quad (5)$$

The program to calculate PDSI is available (previous registration) at:

http://nadss.unl.edu/download/

Table 7 shows the PDSI values and the corresponding drought intensity according to the Palmer (1965) classification system. According to Palmer (1965), a drought event occurs any time the PDSI is continuously negative and reaches an intensity of -2.0 or less. The event ends when the PDSI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month that the event continues.

Table 7 PDSI values and corresponding drought intensity according to Palmer (1965) classification system.

Palmer Classifications	
4.0 or more	extremely wet
3.0 to 3.99	very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	slightly wet
0.5 to 0.99	incipient wet spell
0.49 to -0.49	near normal
-0.5 to -0.99	incipient dry spell
-1.9 to -1.99	mild drought
-2.0 to -2.99	moderate drought
-3.0 to -3.99	severe drought
-4.0 or less	extreme drought

Historically, the most widely used drought index in the United States has been the Palmer Drought Index. Palmer based the index on anomalies in the supply and demand concept of the water balance equation. Inputs into weekly or monthly calculations include precipitation, temperature, and the local antecedent soil moisture conditions. The data are standardized to account for regional differences so that Palmer Drought Severity Index (PDSI) values can be compared from one location to another. Therefore, identical PDSI values, in theory, from any location indicate the same severity of drought, even though actual rainfall deficiencies would be different at the two locations.

7.5 STANDARDIZED PRECIPITATION INDEX (SPI)

McKee et al. (1993; 1995) designed the SPI to be a relatively simple, year-round index applicable to the water supply conditions important to Colorado and as a supplement to information provided by the PDSI and the Surface Water Supply Index. The SPI is based on precipitation alone. Its fundamental strength is that it can be calculated for a variety of time scales. This versatility allows the use of the SPI to monitor short-term water supplies, such as soil moisture, which is important for agricultural production, and longer-term water resources such as ground water supplies, stream flow, and lake and reservoir levels. The ability to examine different time scales also allows droughts to be readily identified and monitored for the duration of the drought.

The Standardized Precipitation Index assigns a single numeric value to the precipitation which can be compared across regions with markedly different climates. The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. Since precipitation is not normally distributed, a transformation is first applied so that the transformed precipitation values follow a normal distribution. The program to calculate SPI can be obtained from:

http://www.drought.unl.edu/monitor/spi/program/spi_program.htm

The method of calculation includes the following steps:

Data preparation. Generation of a time series of the precipitation value of interest is generated. At least 30 years of data are needed.

Determination of a probability frequency distribution that statistically fits the time series of precipitation data.

Calculation of the cumulative probability distribution from the fitted frequency distribution.

Transformation of the frequency distribution to the normal or Gaussian frequency distribution with a mean of zero and standard deviation of one so the values of the SPI are expressed as standard deviations.

Calculation of the number of standard deviations that the precipitation value of interest would be away from the mean, for an equivalent normal distribution and adequate choice of fitted theoretical distribution for the actual data. This value is the SPI.

Interpretation of the SPI index. A particular precipitation total for a specified time period is then identified with a particular SPI value consistent with probability. Because the probability distribution of precipitation is transformed into a normal distribution, the mean SPI for the location and desired period is zero. Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. The magnitude of departure from zero represents a probability of occurrence so that decisions can be made based on this SPI value. Because SPI values fit a typical normal distribution, one can expect these values to be within one standard deviation approximately 68% of the time, within two standard deviations 95% of the time, and within three standard deviations 99% of the time. A related interpretation would be that a SPI value of less than -1.0 occurs 16 times in one hundred years and a SPI of less than -2.0 occurs 2-3 times in one hundred years.

Table 8 shows the SPI values and the corresponding drought intensity according to McKee et al. (1993) classification system. According to McKee et al. (1993), a drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude".

Table 8 SPI values and corresponding drought intensity according to McKee et al. (1993) classification system

SPI Values	Drought Intensity
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	Severely dry
-2 and less	extremely dry

Examples of application and interpretation of the SPI can be found in the Colorado State University website (http://ulysses.atmos.colostate.edu/SPI.html) and in the United States by the National Drought Mitigation Center (http://www.drought.unl.edu/monitor/spi/program/spi_program.htm).

The SPI has a number of advantages over the PDSI. First, it is a simple index and is based only on precipitation. The PDSI calculations are complex (i.e., 68 terms are actually defined as part of the calculation procedure (Soulé, 1992). In spite of the complexity of the PDSI, McKee (1996) believes that the main driving force behind the PDSI is precipitation. Second, the SPI is versatile. It can be calculated on any time scale, which gives the SPI the capability to monitor conditions important for both agricultural and hydrological applications. This versatility is also critical for monitoring the temporal dynamics of a drought, including its onset and end, which have typically been a difficult task for other indices. Third, because of the normal distribution of SPI values, the frequencies of extreme and severe drought classifications for any location and any time scale are consistent. An extreme drought according to this scale (SPI = -2.0) occurs approximately 2-3 times in 100 years, an acceptable frequency for water planning. Fourth, because it is based only on precipitation and not on estimated soil moisture conditions as is the PDSI, the SPI is just as effective during the winter months.

7.6 PALMER HYDROLOGICAL DROUGHT INDEX (PHDI)

In near-real time, Palmer's index is no longer a meteorological index but becomes a hydrological index referred to as the Palmer Hydrological Drought Index (PHDI) because it is based on moisture inflow (precipitation), outflow, and storage, and does not take into account the long-term trend (Karl and Knight, 1985).

7.7 CROP MOISTURE INDEX (CMI)

The Crop Moisture Index (CMI) uses a meteorological approach to monitor week-to-week crop conditions (Palmer, 1968) as is appropriate to evaluate short-term moisture conditions across major crop-producing regions. It is based on the mean temperature and total precipitation for each week, as well as the CMI value from the previous week. The CMI responds rapidly to changing conditions, and it is weighted by location and time so that CMI maps can be used to compare moisture conditions at different locations.

Weekly maps of the CMI are available as part of the USDA/JAWF Weekly Weather and Crop Bulletin (http://www.usda.gov/oce/waob/jawf/wwcb.html).

7.8 SURFACE WATER SUPPLY INDEX (SWSI)

The Surface Water Supply Index (SWSI) has the advantage of combining hydrological and climatic features in a single index and allows for the consideration of reservoir storage. The SWSI is computed for a hydrographic basin or for a water resources system by obtaining the probability of non-exceedance for the values of precipitation, runoff, stored water, and snowpack in the basin (Garen, 1993, Shafer and Dezman, 1982). Each component is assigned a weight depending on local conditions. These weighted components are summed to determine the global SWSI value for the entire basin.

Four inputs are required within the SWSI: snowpack, streamflow, precipitation, and reservoir storage. Because it is dependent on the season, the SWSI is computed with only snowpack, precipitation, and reservoir storage in the winter. During the summer months, streamflow replaces snowpack as a component within the SWSI equation.

The procedure to determine the SWSI for a particular basin is as follows: monthly data are collected and summed for all the precipitation stations, reservoirs, and snowpack/streamflow measuring stations over the basin. Each summed component is normalized using a frequency analysis gathered from a long-term data set. The probability of non-exceedence—the probability that subsequent sums of that component will not be greater than the current sum—is determined for each component based on the frequency analysis. This allows comparisons of the probabilities to be made between the components. Each component has a weight assigned to it depending on its typical contribution to the surface water within that basin, and these weighted components are summed to determine a SWSI value representing the entire basin. Like the Palmer Index, the SWSI is centered on zero and has a range between -4.2 and +4.2.

Monthly SWSI maps for the USA (State of Montana) are available at the Montana Natural Resource Information System (http://nris.state.mt.us/wis/SWSInteractive/).

7.9 RECLAMATION DROUGHT INDEX (RDI)

Like the SWSI, the RDI is calculated at the river basin level, incorporating temperature as well as precipitation, snowpack, streamflow, and reservoir levels as input. The RDI differs from the SWSI in that it builds a temperature-based demand component and a duration into the index. The RDI is adaptable to each particular region and its main strength is its ability to account for both climate and water supply factors.

The RDI was developed by the Bureau of Reclamation to release drought emergency relief funds. Table 4 shows the classification of droughts according to the RDI index. according to the Bureau of Reclamation.

Table 9 Classification of droughts according to the RDI index (Bureau of Reclamation).

RDI Classifications	
4.0 or more	extremely wet
1.5 to 4.0	moderately wet
1 to 1.5	normal to mild wetness
0 to –1.5	normal to mild drought
-1.5 to -4.0	moderate drought
-4.0 or less	extreme drought

7.10 STANDARDISED PRECIPITATION-EVAPOTRANSPIRATION INDEX (SPEI)

The SPEI fulfils the requirements of a drought index since its multi-scalar character enables it to be used by different scientific disciplines to detect, monitor and analyze droughts.

The SPEI allows comparison of drought severity through time and space, since it can be calculated over a wide range of climates, as can the SPI. Moreover, Keyantash and Dracup (2002) indicated that drought indices must be statistically robust and easily calculated, and have a clear and comprehensible calculation procedure. All these requirements are met by the SPEI. However, a crucial advantage of the SPEI over other widely used drought indices that consider the effect of PET on drought severity is that its multi-scalar characteristics enable identification of different drought types and impacts in the context of global warming.

An application of this methodology across Africa can be found in:

Vicente-Serrano et al., (2012) Challenges for drought mitigation in Africa: The potential use of geospatial data and drought information systems. Applied Geography 34 (2012) 471-486

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